Energy Policy 37 (2009) 623–632

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

A longitudinal analysis of the UK transport sector, 1970–2010

Alexandros Gasparatos *, Mohamed El-Haram, Malcolm Horner

Construction Management Research Unit (CMRU), Division of Civil Engineering, University of Dundee, Fulton Building, DD1 4HN, Dundee, UK

ARTICLE INFO

Article history:
Received 6 February 2008
Accepted 2 October 2008
Available online 25 November 2008

Keywords:
Exergy
Atmospheric emissions
Transport

ABSTRACT

This paper presents an overview of the resource consumption and environmental impact of the United Kingdom's transport system for the period between 1970 and 2010. For the purpose of this analysis the concept of exergy has been employed both to quantify and aggregate the energy used and the atmospheric emissions arising from the sector. Our analysis illustrates and elucidates the disproportionate increase of the overall exergy consumed by the transport sector when compared to that of other UK economic sectors. Furthermore, its environmental impact and, in particular, the trends in the emission of the main ambient air pollutants and greenhouse gases is discussed. Exergy efficiency and intensity time series are also calculated and recommendations are made in order to minimize the sector's environmental impact and to facilitate a shift towards a more sustainable transport system.

1. Introduction

The transport sector encompasses a plethora of activities relevant to the mobility of passengers and the movement of freight and as such it plays an important role in the economic activity of a society. However, the transport sector has also been identified as one of the major contributors to the depletion of fossil fuels, the degradation of the environment and the deterioration of human health. Transport activity is a significant source of atmospheric pollutants responsible for the degradation of ambient air quality within urban centres with subsequent effects on human and ecosystem health. Furthermore, transport activity impacts the global environment as it can be blamed for ever increasing emission of greenhouse gases. For example, transport is the second largest contributor of greenhouse gases in the UK (AEAT, 2007). Additionally, transport is a topic of considerable political importance given that it is an integral part of a significant portion of the everyday life of the country's population with household expenditure on transport being third only to housing and food (Glaister, 2002). As a result transport can play an important role for a shift towards sustainability in the UK (Banister, 2005). Considering the above, the aim of this study is to assess both the resource consumption and the environmental impact accruing from transport activity in the UK for the period between 1970 and 2010. The thermodynamic concept of exergy is employed to quantify fossil fuel consumption and atmospheric emissions from different modes of transport.

Exergy, or available energy, is defined as the maximum work that can be obtained from a system as it moves towards thermodynamic equilibrium with a reference state. What makes exergy an ideal analytical tool for energy conversion systems is the fact that, in contrast to energy, it is not conserved. In fact exergy is consumed as a result of unavoidable irreversibilities in any real process. As Dincer (2002) states that "*exergy is the part of energy which is useful in the society and therefore has an economic value and is worth taking care of*".

It has been suggested that exergy is relevant to the first and second laws of Thermodynamics given that it is a measure of both the quantity (1st law) and the quality (2nd law—entropy law) of different energy sources (Dincer, 2002). As a result the exergy of an energy form is a direct measure of its usefulness, quality or potential to cause change. Section 2 contains an explanation of the main concepts employed in our study but for a deeper insight of exergy's theoretical foundations and calculation the reader is referred to Kotas (1985) and Szargut et al. (1988).

Various case studies have employed the concept of exergy at different scales ranging from the process scale (Kotas 1985; Szargut et al., 1988) to the urban (Balocco et al., 2004), sectoral (Dincer et al., 2003; Utlu and Hepbasli, 2007), national (Wall, 1990; Ertesvag, 2001) and supranational scale (Nakicenovic et al., 1996). Given its significant resource consumption and environmental impact, the transport sector has attracted attention from exergy analysts with a number of such studies having been published in the past few years (e.g., Dincer et al., 2004; Ji and Chen, 2006; Utlu and Hepbasli, 2006; Ediger and Çamdali, 2007; Saidur et al., 2007; Koroneos and Nanaki, 2007).

Exergy analysis was initially employed by engineers at the process scale in order to optimize energy conversion. Perhaps the main reason that has influenced analysts to apply exergy analysis to ever larger and more complex systems has been its ability to

* Corresponding author. Tel.: +44 1382 386560; fax: +44 1382 386560.
E-mail addresses: a.gasparatos@dundee.ac.uk (A. Gasparatos), m.elharam@dundee.ac.uk (M. El-Haram), r.m.w.horner@dundee.ac.uk (M. Horner).

0301-4215/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2008.10.001

provide answers that can inform energy policy making. Some of the key points regarding its relevance to energy policy makers have been highlighted by Dincer (2002). Exergy analysis, amongst others, can

- comment on the impact of resource utilization on the environment;
- assist the design of energy systems;
- promote efficient resource use;
- play a pivotal role for ensuring a sustainable future.

The real strength and weakness of exergy analysis lies in the fact that it is one of the few techniques that can assess resource use, degradation and environmental impact using a common denominator. Rosen et al. (2008) suggest three links between exergy and environmental impact; order destruction, resource degradation and waste exergy emissions. Rosen and Dincer (1999) state that waste emissions (including atmospheric emissions) posses exergy as a result of their being in disequilibrium with the reference environment due to their different chemical composition to that of the environment. This disequilibrium is a measure of the waste stream's potential to cause change, or negatively impact the environment in this case. However, according to Cleveland et al. (2000) the exergy of wastes and pollutants is no more than a rough first-order approximation of environmental impact because it does not vary with the specific properties (e.g., toxicity) of the waste material. Nevertheless, this attribute of exergy analysis can be used in order to elucidate the environmental impact of transport activities. Potential correlations between exergy consumption (total and by mode) and atmospheric emissions (total and by mode) can also provide insights on whether the environmental impact of transport activity has been decoupled from its volume.

Central to exergy analysis is the concept of exergy efficiency. Ulgiati et al. (2006) claim that the concept has a relationship with the market logic as it can be used to optimize processes. Rosen and Dincer (2001) suggest that an increase in exergy efficiency would imply a decrease of environmental impact (exergy conversion with fewer losses and exergy emissions) and a simultaneous increase in sustainability (process approaches reversibility). The attributes of exergy discussed in the previous paragraphs are the main reason why scientists and engineers have suggested that more meaningful thermodynamic efficiencies can be obtained through exergy analysis than through energy analysis.

However we believe that what constitutes exergy analysis topical for energy policy advice, particularly in the UK context, is its link with the concept of sustainable development and the increasing fears of fuel scarcity.

In order to appreciate these links its origins should be properly understood. Thermodynamic accounting tools (initially energy analysis and subsequently exergy analysis) gained momentum after the oil crises of the 1970s and 1980s (Hammond, 2004a). Increasing fossil fuel scarcity during that period rendered the development of tools that could account for energy in a physical manner imperative. However, the two oil crises, apart from influencing the development of energy accounting tools, made the exploitation of the N. Sea oilfields economically feasible. The UK thus became one of the few European nations with significant such resources and a degree of energy security. However, over the past years diminishing output from these fields, the fact that UK has become a net importer of petroleum products and the international energy situation brings once more the issue of energy security into the UK public agenda. Increasing concerns over fossil fuel scarcity will undoubtedly render the insights provided by thermodynamic analyses, and particularly by exergy analysis, important for the development of policies aspiring to more efficient energy use.

A second reason why exergy analysis is topical is the increasing prominence of sustainable development in the public debate. Both the European Union and the UK have identified sustainable development as a key element of their future development strategies. For example in the Lisbon Treaty it has been explicitly stated that the member states are "...*determined to promote economic and social progress for their peoples, taking into account the principle of sustainable development*" (EC, 2008, p. C115/16). Sustainable development has also been a key consideration within UK government policies as the high level UK sustainable development strategy exemplifies (DEFRA, 2005). This document considers transport as a priority area for ensuring a sustainable future within the UK. From such high level documents the concept has trickled down and the term sustainable transport seems to have become a new buzzword and an all encompassing term to denote socially and environmentally friendly modes of transport. From this starting point, a number of initiatives have been conceived by the UK Department for Transport to promote sustainable transportation.

Exergy analysis can provide policy advice that is relevant to sustainable development and to sustainable transport, particularly concerning transport's environmental impact. As has been shown in the academic literature, (e.g., Bastianoni and Marchettini, 2000; Bastianoni et al., 2005; Hammond, 2004a, b), exergy analysis can be relevant to different frameworks that attempt to operationalise sustainable development such as the Natural Step (e.g., TNS, 2000) and Herman Daly's operational principles of sustainability (Daly, 1990). Other aspects of sustainable development that can be captured by exergy analysis such as the triple bottom line, equity consideration and the precautionary principle, amongst others, have been discussed by Gasparatos et al. (2008; in press a).

Insights provided by our exergy analysis will be used to elucidate the reasons behind the observed changes in fossil fuel consumption and atmospheric emissions as well as to suggest potential policy instruments that could result in more sustainable modes of transport.

2. Methodology

Exergy can be "...split into a number of constituents, i.e. its thermodynamic, chemical, kinetic, potential, nuclear...'components', each one of which can be exactly and deterministically related to the state properties of the system and to a reference 'environment'" (Sciubba and Ulgiati, 2005). It has been suggested that for the fuels used in the transport system only chemical exergy is significant (Kotas, 1985; Ji and Chen, 2006). The chemical exergy of a fuel can be derived from Eq. (1)

$$e_c = \text{LHV} \times \gamma \quad (1)$$

where e_c is the specific chemical exergy of the fuel (in J/g), LHV is the lower heating value of the fuel (in J/g), and γ is a factor which is essentially an exergy–energy ratio that depends on the chemical properties of the fuel and can be calculated according to the procedure explained by Kotas (1985). LHVs and γ for the different type of fuels used in our study are included in Table 1.

As has been discussed in the Introduction thermodynamic efficiencies are key outputs of an energy and exergy analysis. Generally speaking energy efficiency (first law efficiency) and exergy efficiency (second law efficiency) are defined as

$$n = \text{work/energy input} \quad (2)$$

Table 1
Lower heating values (LHVs) and exergy factors for selected fuels.

Fuels	LHVs[a]	Exergy factors[b]
Coal	26.0 GJ/tonne	1.06
Petroleum products	43.6 GJ/tonne	1.06
Natural gas	35.6 MJ/m^3	1.04
Coke	29.8 GJ/tonne	1.05
Coke oven gas	16.2 MJ/m^3	1.04
Electricity	–	1
Fuelwood (20% humidity)	10.0 GJ/tonne	1.11
Landfill and sewage gas	21.0 MJ/m^3	1.13
Waste	–	1.11

[a] Source: (BERR, 2007e; DTI, 2006).
[b] Source: (Kotas, 1985; Ertesvag and Mienik, 2000; Utlu and Hepbasli, 2007; Gasparatos et al., in press b).

$$\psi = \text{work/exergy input} \quad (3)$$

$$\psi = n/\gamma \quad (4)$$

where γ is the exergy factor.

According to Ji and Chen (2006), the denominators in Eqs. (2) and (3) denote the work that is performed by the vehicle in order to overcome the drag force due to the ambient fluid or/and overcome the friction with the ground. As a result, and considering the plethora of modes and fuels employed in a country's transport sector, the overall exergy efficiency of a transport system for a given year is provided by Eq. (5)

$$\psi = \sum_{i,j} [(n_i/\gamma_j) \times \mathrm{fr}_{ij}] \quad (5)$$

where n_i is the energy efficiency of the ith mode of transport, γ_j the exergy factor of the jth energy source and fr_{ij} the exergy fraction of the jth energy source.

In order to assess the effectiveness of the different transport modes and of the sector as a whole two measures of exergy intensity are considered in this study; exergy consumption intensity and exergy emission intensity. The former is a measure of the exergy consumed per converted turnover (CT) (Eq. 6) and the second is a measure of the total exergetic content of the atmospheric pollutants emitted per CT (Eq. 7).

$$\mathrm{ExCT}_{\mathrm{con},i} = \mathrm{Ex}_{\mathrm{con},I}/\mathrm{CT} = \mathrm{Ex}_{\mathrm{con},I}/(\mathrm{FTK} + C \times \mathrm{PK}) \quad (6)$$

$$\mathrm{ExCT}_{\mathrm{em},i} = \mathrm{Ex}_{\mathrm{em},i}/\mathrm{CT} = \mathrm{Ex}_{\mathrm{em},i}/(\mathrm{FTK} + C \times \mathrm{PK}) \quad (7)$$

where $\mathrm{ExCT}_{\mathrm{con},i}$ is the exergy consumption intensity of the ith mode of transport; $\mathrm{Ex}_{\mathrm{con},i}$ is the exergy consumed by the ith mode of transport; $\mathrm{ExCT}_{\mathrm{em},i}$ is the exergy emission intensity of the ith mode of transport; $\mathrm{Ex}_{\mathrm{em},i}$ is the exergy emitted by the ith mode of transport; FTK denotes freight ton km; PK denotes passenger km; C is the conversion coefficient between FTK and PK that for the purpose of the paper was assumed as 0.09t (assumes passengers weighing an average of 70 kg and carrying 20 kg of luggage).

3. Data retrieval and manipulation

Time series for energy consumption by fuel for all final energy users were collected from BERR (2007a). Generally speaking time series were complete for all fuels between 1970 and 2006 with the exception of heat sold (mainly from combined heat and power plants and from community heating schemes) and renewable energy carriers (wood, waste, active solar, sewage and landfill gas, etc). Furthermore, breakdowns by renewable energy source were available only from 1998 onwards BERR (2007b). For heat sold, the earliest reported figures (1998) were used for the period 1970–1997. For renewable energy the breakdown by renewable energy source in 1998 was used for the previous years. Furthermore, it as also assumed that the overall energy consumption from renewables during the period 1970–1987 was the same as for the year 1988. Even though these assumptions create a source of uncertainty in our calculations they are not expected to affect the final results significantly given the small significance of these two energy sources in the UK energy system. Heat and renewables accounted for roughly 2.1% of overall energy consumed in 1998.

Time series for transport energy consumption by fuel and mode of transport were collected from BERR (2007a). These time series were complete with the exception of electricity used in rail transport where the official statistics from 1990 onwards include the electricity used in transport premises. Data on the actual electricity used for traction purposes were collected for 2003–2006 (BERR, 2007c) and the figures reported in 2003 were used for the period between 1990 and 2002. Given the small significance of electricity in the UK transport system (refer to Section 4.1) this assumption is again not expected to have a significant impact.

Exergy efficiency was calculated following the methodology outlined in Eq. (5). Energy efficiencies of the different modes of transport were collected from Hammond and Stapleton (2001) and Gasparatos et al. (in press b) and were 29% for rail, 17% for road, 25% for water and 27% for air transport.

Freight and passenger statistics were collected from (DfT, 2007a; DTI, 2006) with complete time series being reported for most modes of transport. The only exception was passenger movement (in PK) by water transport that was not reported at all. Water transport contribution in passenger movement was instead calculated through the number of passengers in domestic trips and their accompanying vehicles as reported for the period 1998–2006 by DfT (2007b). For calculating the PK the number of passenger undertaking each trip was multiplied by the length of the trip. Furthermore the ton km for the accompanying vehicles/buses was also considered. Again, the small contribution of sea transport for passenger movement and their accompanying vehicles (estimated $\approx$0.1% of the overall passenger movement in 2006) is not expected to create significant uncertainty to the overall figures reported in our analysis. It should be noted here that only domestic passenger and freight transport was considered.

Atmospheric pollutants that were considered in our study include CO_2, CH_4, SO_2, CO, C_6H_6, NOx (assumed as NO), HF, As, Cd, Ca, Cr, Cu, Pb, Mg, Hg, Ni, K, Se, Na, V and Zn. The exergy of particulate matter (PM) and Non-Methane Volatile Organic Compounds (NMVOC), apart from C_6H_6, was not quantified due to lack of information concerning their chemical composition. Analysed time series for all pollutants were for the period 1970–2005. All these time series were collected from (NAEI, 2007) and the chemical exergies of the pollutants from Kotas (1985) and Szargut et al. (1988). It is worth mentioning here that our results include not only estimates of emissions resulting from inland transport but also from international aviation and maritime within the UK territory. Cases where pollution from international aviation and maritime was considered in our calculations have been highlighted in the text.

4. Analysis

4.1. Resource consumption

Various energy sources have been used for transport within the UK since 1970. Fossil fuels such as coal, coal derived fuel, coke and petroleum products and electricity have been the predominant energy sources. However, with the exception of petroleum and electricity, all other energy sources have become obsolete since the beginning of the 1990s. Petroleum products have consistently been the single most important energy source accounting for 98.4% (an all time low) of the overall exergy consumed by the transport sector in 1970 gradually rising to 99.6% (an all time high) in 2006.

Overall exergy consumption in the transport sector has risen sharply from 1249.8 PJ in 1970 to 2630.9 PJ in 2006, which corresponds to a 110.5% increase. The relevant figures for energy consumption were 1179.9 PJ in 1970, 2472.1 PJ in 2006 which corresponded to a 109.6% increase. This increase seems to be disproportionate with that of all other energy end-users combined (i.e. industry, domestic, agriculture, services and transport) that show a 6.5% rise in the amount of exergy consumed from 6446.7 PJ exergy to 6866.5 PJ exergy over the same period. Trends in the overall energy consumed were similar with a 6.6% increase in the amount of energy consumed from 6218.3 PJ of energy in 1970 to 6628.4 PJ of energy in 2006. What is more important though is that for all other energy end-users, apart from transport, the overall exergy consumption has decreased by 18.5% in the study period (from 5196.9 PJ to 4235.6 PJ exergy). In a similar manner, energy consumption in all other sectors decreased from 5038.6 PJ 1970 to 4156.3 PJ energy in 2006 (a 17.5% decrease). The above results imply that transport has single handedly been responsible for the increase in overall exergy and energy consumption within the UK over the past 36 years. The exergy trends are illustrated in Fig. 1 and the energy trends in Fig. 2.

Exergy consumption in the transport sector is expected to continue increasing according to many scenarios (BERR, 2007d). For example, according to the central GDP growth–high fuel prices (CH) scenario the overall exergy increase from 2006 to 2010 will be in the order of 9.5% (to 2880.3 PJ). According to the central GDP growth–low fuel prices (CL) scenario there is an expected 12.3% increase (to 2955.7 PJ). It is worth mentioning that an extrapolation of the trend for the period 1991–2006 established in Fig. 1 implies an overall exergy consumption of 2738.4 PJ in 2010. It should also be noted here that both these scenarios overestimated the 2005 consumption in the transport by 0.9% (CH) and 3.5% (CL) respectively.

Our analysis, follows the official statistics' breakdown and has accounted for four main modes of transport, namely rail, road, water and air transport. Road transport has traditionally been the largest consumer of exergy averaging 77.7% of the overall exergy consumed by the transport sector during the whole period with air (16.6%), water (3%) and rail transport (2.7%) following. With the exception of rail transport all other modes have increased their overall exergy and energy consumption over the past 36 years (Fig. 3 for exergy time series). In more detail, road transport increased its overall exergy consumption by 98.4% (from 950.8 PJ to 1886.6 PJ), water transport by 42.5% (from 56.5 PJ to 80.4 PJ) and air transport by a massive 261.8% (from 171.7 PJ to 621.3 PJ). Rail transport, on the other hand, experienced a reduction in its overall exergy consumption by 39.8% (from 70.9 PJ to 42.7 PJ). These trends are summarized in Figs. 4 and 5 for exergy and energy respectively. Regarding energy consumption there has been an increase of 98.4% (from 897.0 PJ to 1779.8 PJ energy) for road transport, an increase of 42.5% for water transport (from 53.3 PJ to 75.9 PJ energy) and an increase of 261.8% (from 162.0 PJ to 586.1 PJ energy) for air transport. As in the case of exergy consumption rail transport showed a decrease of 54.9% in energy consumption (from 67.4 PJ to 30.4 PJ energy) for the period of study.

In contrast to exergy and energy consumption, the exergy/energy efficiencies of the transport sector do not follow a consistent trend. Specifically, there is an observed decrease of the overall exergy efficiency from 18.3% in 1970 to an all time low of 17.9% in 1991. Since 1991 the overall exergy efficiency has been consistently increasing, reaching the all time high of 18.7% in 2006. Energy efficiency for the whole sector follows similar trends: it was 19.4% in 1970, 18.9% in 1991 and 19.8% in 2006. These trends of exergy and energy efficiency are illustrated in Fig. 6 and can be explained quite easily. Looking at the percent

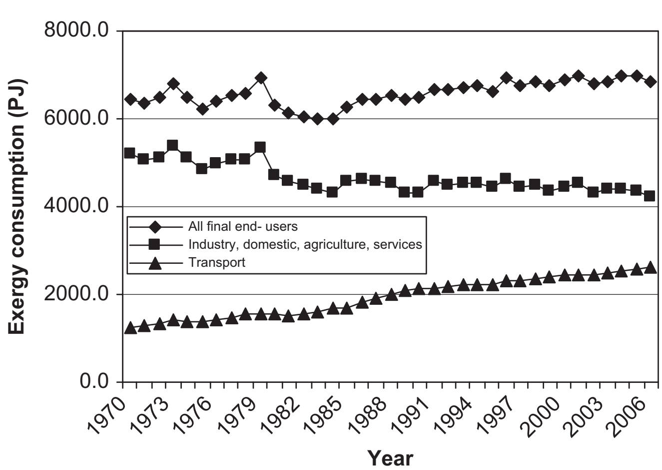

Fig. 1. Final exergy consumption by end users.

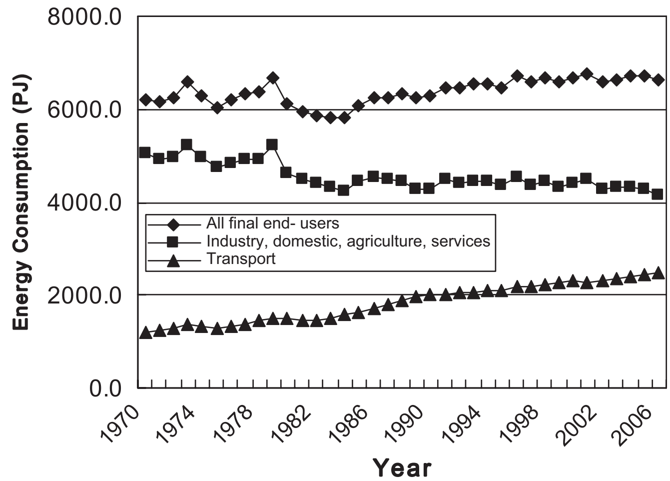

Fig. 2. Final energy consumption by end users.

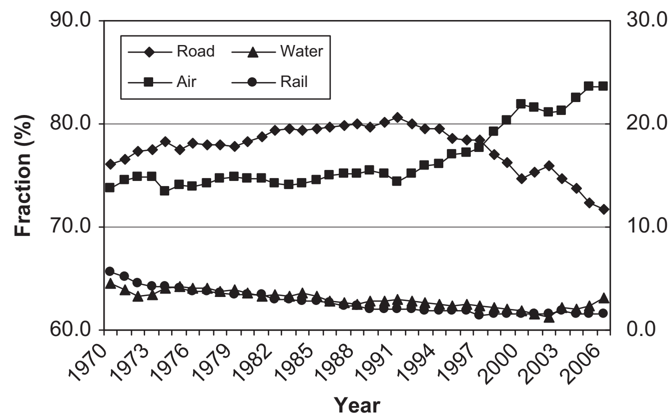

Fig. 3. Fraction of exergy consumption by mode of transport. *Note*: Right y-axis refers to air, water and rail transport.

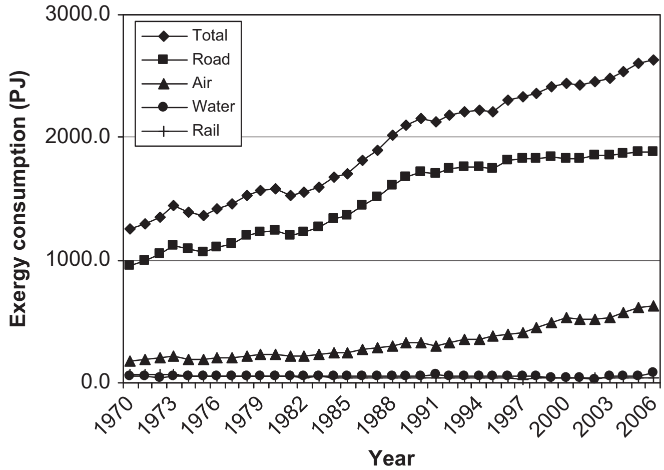

Fig. 4. Exergy consumption by mode of transport.

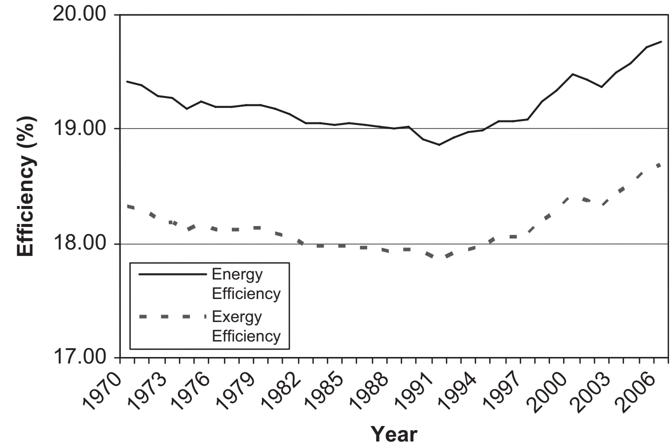

Fig. 6. Exergy efficiency by year.

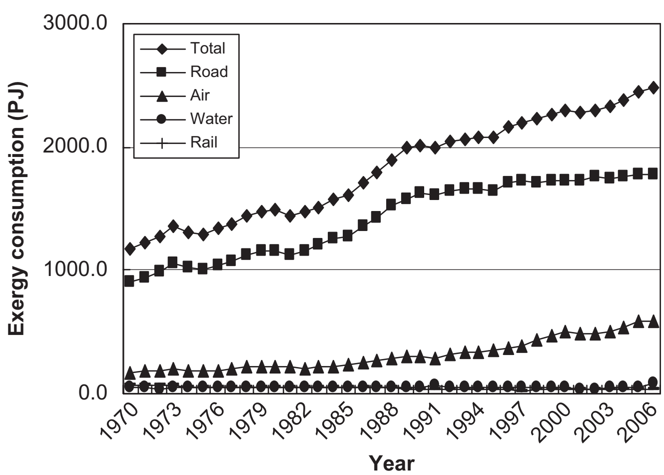

Fig. 5. Energy consumption by mode of transport.

exergy consumption for each means of transport (Fig. 3) it is evident that from 1970 to 1991 there is consistent increase of the fraction of exergy consumed by road and air transport (rail transport shows a consistent decrease while water transport exhibits a much more random trend). However, from 1991 the percentage of road transport is gradually declining while that of air transport is continuing to increase. Considering now the much higher energy efficiency of air transport (27%) when compared with that of road transport (17%) it is evident that the overall increase in exergy efficiency is driven by this increasing prominence of air transport. The same reasons lie behind the changes in energy efficiency. These increases in exergy and energy efficiencies are a mixed blessing as will be explained in Section 4.2.

Exergy consumption intensity for the whole transport sector has increased by 10.3% between 1970 and 2006 (from 7.4 PJ/Gtkm to 8.1 PJ/Gtkm). Exergy consumption intensities for road transport have marginally decreased by 0.2% (from 8.09 PJ/Gtkm to 8.07 PJ/Gtkm) with the other modes of transport having experienced more significant decreases. Specifically exergy consumption intensities decreased by 37.3% (from 2.5 PJ/Gtkm to 1.6 PJ/Gtkm) for rail transport, by 29.7% (from 953.9 PJ/Gtkm to 671.0 PJ/Gtkm) for air transport and by 45.8% (from 2.4 PJ/Gtkm to 1.3 PJ/Gtkm) for water transport. From the above statistics it is evident that air transport consumes over one hundred times more for each tkm than other modes of transport. This huge exergy consumption intensity of air transport coupled with its increasing prominence over the past years (as discussed in Fig. 3) is the main reason why exergy consumption intensity for the whole sector has increased since 1970 despite decreases in exergy consumption intensity for all individual modes of transport over the same period. Trends of the exergy and energy consumption intensities for the different transport modes and of the transport sector as a whole are illustrated in Figs. 7 and 8 respectively. Results for energy consumption intensity follow similar trends. The overall energy consumption intensity increased by 9.8% (from 7.0 PJ/Gtkm in 1970 to 7.7 PJ/Gtkm in 2006). Energy consumption decreased marginally for road transport by 0.2% (from 7.63 PJ/Gtkm to 7.62 PJ/Gtkm) and more significantly for all other sectors; 53.0% for rail transport (from 2.4 PJ/Gtkm to 1.1 PJ/Gtkm), 45.8% for water transport (from 2.3 PJ/Gtkm to 1.2 PJ/Gtkm) and by 29.7% for air transport (from 899.9 PJ/Gtkm to 633.0 PJ/Gtkm).

4.2. Environmental impact

The overall exergy content of the atmospheric pollutants emitted by transport was 93.6 PJ in 2005, a decrease of 8.7% from 1970 levels. It should be noted that these figures include atmospheric emissions from international transport activities within the UK (air, maritime). Atmospheric emission from purely domestic activities decreased by 17.4% (from 88.9 PJ to 73.4 PJ) in the same period. This decrease is not consistent for all pollutants as will be explained later so a de-coupling between transport activity and environmental impact cannot be implied. This decrease can be attributed to a certain extent in the technical standards for fuels and combustion engines mainly for road transport. It must be noted that this observed decrease, albeit encouraging, is much lower than the overall decrease of the exergy content of atmospheric emissions arising from all other economic sectors (a 46.7% decrease in the same period). Relevant data are included in Fig. 9.

Emissions from road transport have decreased over time despite the significant increase of the overall exergy consumed by it. Specifically there was a 19.7% decrease of the total exergy of the emitted gases (from 84.7 PJ in 1970 to 68.1 PJ in 2005). A more substantial decrease of 51.0% is observed in water transport (from 12.7 PJ to 6.2 PJ). On the other hand rail and air transport have been responsible for emitting an increasing amount of atmospheric pollutants. This corresponded to an increase of 24.0% from

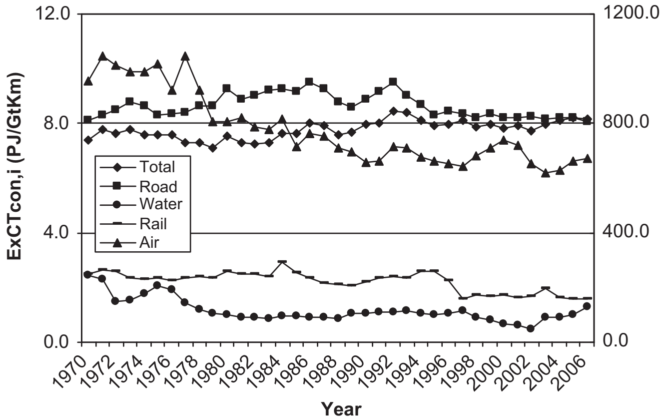

Fig. 7. Exergy consumption intensities for different modes of transport. *Note*: Right y-axis refers to air transport.

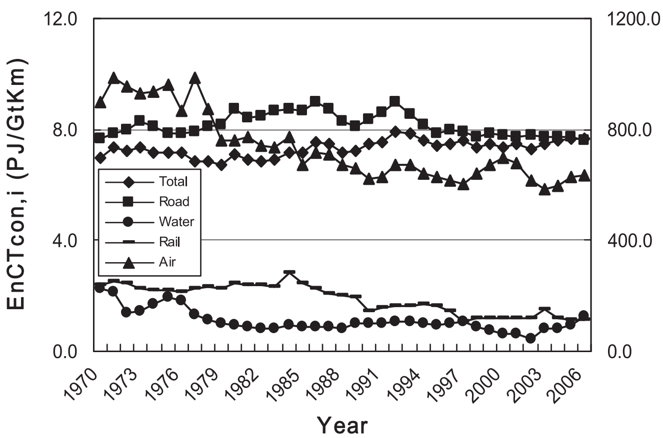

Fig. 8. Energy consumption intensities for different modes of transport. *Note*: Right y-axis refers to air transport.

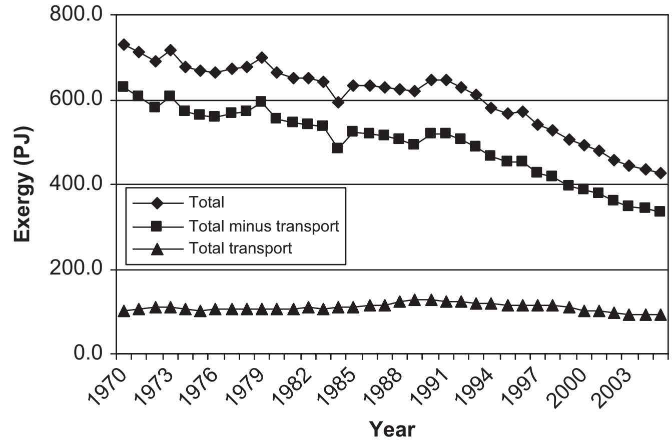

Fig. 9. Atmospheric emissions by end user.

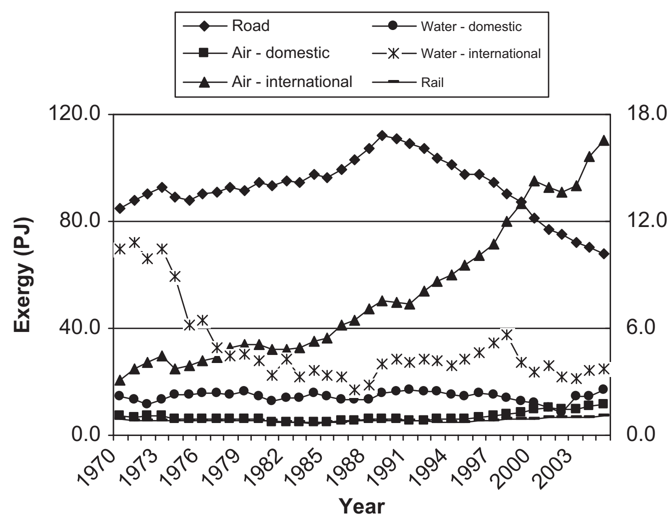

Fig. 10. Atmospheric emissions by mode of transport. *Note*: Right y-axis refers to air transport.

rail transport (from 0.9 PJ to 1.1 PJ) and a massive 331.4% from air transport (from 4.2 PJ to 18.2 PJ). This increase in exergy emissions from air transport was more due to international flights (exergy emitted up by 429.3% since 1970 to 16.5 PJ in 2005) than to domestic flights (up by 55.6% since 1970). Relevant time series are included in Fig. 10.

By exploring the links between exergy consumption by mode of transport with the resulting atmospheric pollution several interesting insights can be gained. First of all, there seems to be no correlation between exergy consumption and atmospheric emissions for rail transport. For air transport there seems to be a strong positive correlation between consumed exergy and atmospheric emissions with a correlation coefficient of 0.9782 from 1982 onwards. The situation is similar for water transport with a strong positive correlation of 0.9918 between consumed and emitted exergy for the period 1970–2005. For road transport the situation is more complex. As it is evident from Fig. 10 atmospheric emissions from road transport seem to have peaked around 1991–1992 but exergy consumption has been increasing uninterrupted since 1970. Correlations between exergy consumption and atmospheric pollution for the periods 1970–1990 and 1991–2005 show a positive correlation for the first period (correlation coefficient 0.9826) and a negative correlation for the second period (correlation coefficient −0.9129). In our opinion the main cause for this trend has been the adoption of the European Union emission standards for road vehicles that has been implemented from 1992 onwards. What gives further credibility to this hypothesis is the long term trends of the pollutants covered by the emission standards, namely NO*x*, CO, hydrocarbons (C_6H_6 and CH_4 in our study) and PM (not considered in this study). For the period between 1970 and 1991 there has been a moderate increase in the overall exergy of these pollutants by 3.3% while at the same time there was a massive increase of consumed exergy by 79.9% (averaging a 3.1% increase per year). On the other hand from 1992 onwards there was a moderate increase of 7.7% in exergy consumption (averaging 0.6% per year) and a 76.6% decrease in the exergy of the pollutants covered by the EU emission standards. It should be noted here that in 1991 these pollutants accounted for 54.3% of the total exergy of the emissions coming from road transport and for only 19.4% in 2005. Other factors that might have exerted an influence are the economic recession in the early 1990s (which coincides with the enforcement of the EU emission standards) and the increase in fuel prices during 2000 (Glaister, 2002). The long term trends of the other atmospheric emissions (of which CO_2 in the most prevalent) follow the general exergy consumption patterns and increased by 98.7% between 1970 and 1991 and by 8.0% between 1992 and 2005 (a notable exception being Pb which has decreased dramatically following the implementation of fuel standards).

Exergy consumption and CO_2 emissions from domestic transport are as expected almost perfectly correlated for the whole period (correlation coefficient 0.9934). CO_2 emissions rose by 94.7% from transport activities between 1970 and 2004 (from 18.1 to 35.3 MtC). This increase stems from the fact that, in contrast to traditional air pollutants, no technologies capable of reducing transport CO_2 emissions exist at the moment. According to Tapio et al. (2007) traditional approaches to reduce transport's CO_2 emissions revolve around the use of alternative fuels, greater efficiency in energy use, increased occupancy and load factors as well as smaller distances traveled. Even though there seems to be a modest improvement in some of these factors for the great majority there has not been an improvement. For example biofuels still make a limited impact despite the optimism of the UK government that it will achieve the EU Biofuels Directive requirements by 2010 (Banister, 2007). Since 1980 the average length of haul has risen by 31.0% for road transport (to 87 km in 2005), by 75.0% (to 210 km in 2005) for rail transport and by 15.9% (to 458 km) for water transport (DfT, 2007c). Seat occupancy for private cars has decreased from 1.67 in 1973 to 1.58 in 2005 (DTI, 2006; DfT, 2007c) while the domestic road freight loading factors fell by 9% between 1982 and 2005 (DfT, 2007c). Fuel efficiency for new cars has risen by 23.2% from 9.8 L/100 km in 1978 to 7.5 L/100 km in 2005 (DTI, 2006; DfT, 2007c). Energy efficiency of lorries on the other hand has actually fallen since 1985 by 2.4% for rigid lorries and 21.7% for articulated vehicles (DTI, 2006). Given that exergy consumption is expected to increase in the transport sector, CO_2 emissions are bound to increase as well. Different scenarios published by (BERR, 2007d) show a significant increase for road transport emissions and a much smaller increase for the other modes of transport.

In contrast to exergy consumption intensity (refer to Section 4.1) the exergy emission intensity for the whole of the transport sector decreased by 56.0% between 1970 and 2005 (from 0.53 PJ/Gtkm to 0.23 PJ/Gtkm). Apart from the rail sector all other sectors have experienced a significant decrease in their exergy emission intensities. In more detail, there was a 58.8% decrease (from 0.72 PJ/Gtkm to 0.30 PJ/Gtkm) for road transport, a 69.7% decrease (from 6.2 PJ/Gtkm to 1.9 PJ/Gtkm) for air transport and a 56.3% decrease (from 0.09 PJ/Gtkm to 0.04 PJ/Gtkm) for water transport. Exergy emission intensity for rail transport increased by 32.9% (from 0.03 PJ/Gtkm to 0.04 PJ/Gtkm) in the same period. Despite this increase, rail transport emits the least when compared to the other modes of transport. Fig. 11 summarizes these results.

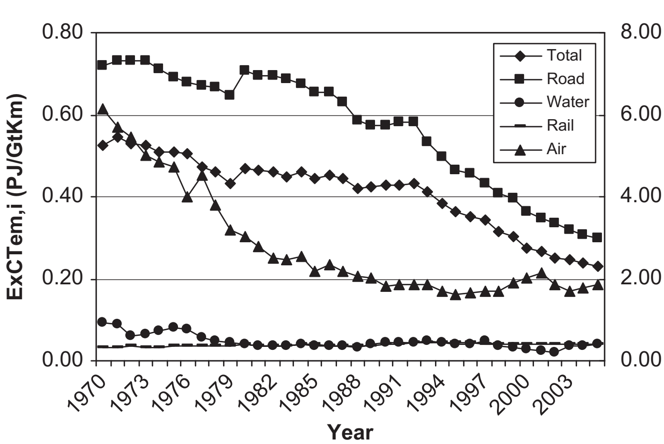

Fig. 11. Exergy emission intensities for different modes of transport. *Note*: Right y-axis refers to air transport.

5. Discussion

Before proceeding to the main discussion of the results, it is important for the reader to appreciate the different viewpoint of exergy analysis to that of traditional economic analysis. At the core of this lies the fact that biophysical models in general, and exergy analysis in particular, employ a different concept of value (cost of production theory) than that of traditional economic analysis (subjective preference theory) (Patterson, 1998; Farber et al., 2002; Gasparatos et al., in press a). This perspective tends to be ecocentric in nature and comes in contrast to the anthropocentric perspective adopted by economic analysis. As a result exergy analysis considers as more appropriate, policies and technological solutions that result in the minimum amount of resources consumed and pollutants emitted regardless of human preferences (Cleveland et al., 2000). Thus the effect of a policy on natural capital becomes the main criterion/yardstick for deciding the acceptability of the policy, something that is more akin to the vision of strong sustainability (Gasparatos et al., 2008).

Accounting for natural resources consumed in a biophysical manner, is expected to promote strategies that safeguard their conservation and their efficient use. In the authors' opinion exergy analysis will bring to the forefront a demand for closer integration of transport policy with other policy objectives, particularly resource conservation and environmental impact, that that have been decoupled from the UK transport policy in the past (refer to Begg and Gray, 2004). This integration might be the key for shifting to a more sustainable transport system.

Our results are summarized in Table 2 and show a significant increase in the overall exergy consumed by transport activities from 1970 (110.5%) onwards with all transport modes (except rail) having significantly increased their overall exergy consumption over time. Road transport is spearheading this trend (98.4% increase) given its prominence in UK's transport system. According to Begg and Gray (2004) rising car ownership, decreasing family size and structure, dispersal of the work/ shopping/social/ etc facilities, fall in motoring costs and new working practices are all contributing factors for this increasing car dependence.

Table 2
Summary of the results.

	Sector	Road	Rail	Water	Air
Exergy consumed					
2006 levels (J)	2630.9	1886.6	42.7	80.4	621.3
1970–2006 change (%)	110.5	98.4	−39.8	42.5	261.8
Energy consumed					
2006 levels (J)	2472.1	1779.8	30.4	75.9	586.1
1970–2006 change (%)	109.6	98.4	−54.9	42.5	261.8
Exergy consumption intensity					
2006 levels (PJ/Gtkm)	8.1	8.07	1.6	1.3	671.0
1970–2006 change (%)	10.3	−0.2	−37.3	−45.8	−29.7
Energy consumption intensity					
2006 levels (PJ/Gtkm)	7.7	7.6	1.1	1.2	633.0
1970–2006 change (%)	9.8	−0.2	−53.0	-45.8	−29.7
Exergy emitted (domestic transport)					
2005 levels (PJ)	73.4	68.1	1.1	2.5	1.7
1970–2005 change (%)	−17.4	−19.7	24.0	15.5	55.6
Exergy emission intensity (domestic transport only)					
2005 levels (PJ/Gtkm)	0.23	0.30	0.04	0.04	1.9
1970–2005 change (%)	−56.0	−58.8	32.9	−56.3	−69.7

Interestingly enough, despite this car dependence, air transport shows the greatest overall exergy consumption increase in relative terms (268.1%). This massive increase of air activity seems to be affecting the exergy efficiency of the transport sector to a great extent. Exergy efficiency increased by 0.8%, since 1991, for the transport sector as a whole which seems to be a positive sign for the conservation of fossil fuel and a lower environmental impact (refer to introduction). The increasing fuel efficiency of road vehicles in the wake of EU policies has surely affected to an extent this trend. However the increasing levels of air transport combined with the much higher exergy efficiency of air transport when compared to that of road transport seem to be the main responsible for that shift. In our opinion, and as a result, the increasing exergy efficiency has been more a result of coincidence than of careful transport planning. Furthermore, the significantly higher exergy consumption and emission intensities of air transport (refer to Figs. 7 and 10 and Table 2) when compared to that of other forms of transport imply that the positive effects of exergy efficiency can be offset by increased environmental degradation and resource consumption in the long run.

One approach to boost the overall exergy efficiency of the sector with a simultaneous long term decrease of the environmental impact would be the promotion of rail transport for passenger and freight movement. Rail transport, despite increases in its exergy emission intensity (exergy emitted per tkm) by 32.9% still had better performance when compared to road and air transport. Careful regulation, akin to that of road transport, coupled with technological innovation could reduce further exergy consumption and emission intensities while better planning could improve the economic benefits to the public. Given that increasing the mobility (rather than reducing the traffic) has been at the centre of the UK Government's transport policy the development of high-speed train links between major cities and the modernization of urban and peri-urban rail systems might contribute to a modal shift that could further increase exergy efficiency and potentially reduce resource consumption and environmental impact in the long run.

A very significant policy implication is the fact that atmospheric pollutants can contribute both to air quality and climate change. Air pollutants such as ozone, PM, NO*x* and SO_2 can in their own right have direct or indirect impacts (both positive and negative) on the climate (AQEG, 2007). As a result policy makers increasingly need to draft policies that can strike a balance between both these considerations which at points might be at odds. As was shown in Section 4.2, technical innovation in road transport sparked by environmental regulation targets has been quite successful in limiting the emission of certain atmospheric pollutants despite the significant increase in transport activity. However, there has not been any significant success in curbing CO_2 emissions and there seems to be little hope that technological innovation alone will be enough to reach the already established emission objectives, especially for road transport. For example, the European Commission proposals for further decreasing the carbon content of fuels through increasing their biofuel content might encounter resistance by UK policy makers fearing that increasing biofuel content can: result in reduced food production (DfT, 2007d); have major adverse environmental impacts such as deforestation (ibid); have no discernible effect due to consequent increases in N_2O emissions from agriculture (Crutzen et al., 2008). Furthermore, given the adverse effect of biofuels in vehicle efficiency it seems that the already established biofuel content target ought to be revised upwards in order to achieve the 1 Mt CO_2 saving per year, thus taking a toll on the overall cost of the policy. Further evidence produced by the OECD urges a shift from biofuel based policies both in national and international contexts due to their adverse sustainability impacts and limited benefits (Doornbosch and Steenblik, 2007).

The potential failure to reach established limits through technical innovation becomes more apparent considering the difficulty of car manufacturers to reach the 140 g CO_2/km target for 2008 and the even more ambitious target of 130 g CO_2/km for 2012 through technical means. During 2006, cars sold within the EU and the UK emitted on average 160 g CO_2/km and 167 g CO_2/km respectively (T&E, 2007) implying that to reach the 2008 target much less the 2012 through technological innovation alone is almost impossible. The car industry's response is quite illuminating as it claims that such a decrease would only be possible through a range of measures including biofuels, CO_2-based car tax and driver training. Technological innovation has long been the main tool employed by the UK government in order to address environmental impact from the road transport sector. It has surely helped a lot but our analysis shows ever smaller annual exergy emission intensity reductions (in percent) suggesting the technological saturation or the diminishing cost-effectiveness of end-of-pipe measures. That is particularly true for road and air transport (albeit to a lesser degree) and it implies that it will not be enough to address the escalating problems of fossil fuel depletion and environmental impact through end-of-pipe measures alone. Policy instruments that could reduce the need for travel as well as the shift of demand to less carbon intensive modes of transport would be an important weapon for tackling such issues.

Finally, increasing exergy consumption in air and water transport coupled with decreasing exergy consumption/emission intensities and high positive correlation factors between exergy consumed and exergy emitted (refer to Table 2) imply that technological innovation has not been enough to decouple transport activity from its environmental impact for these two modes. However water transport primarily, and air transport secondarily are the sectors where technological solutions can have the most discernible impact. Tighter environmental standards through regulation as in the case of road transport can go a long way towards reducing environmental impact from these modes of transport. Other non-technical solutions have also been mooted but to no effect. For example, one of the proposals to curb CO_2 emissions from aviation has been to include it in the European Trading Scheme (ETS). Nevertheless there is a growing disenchantment with this option as it is believed that the pricing signal will be too weak to affect customers (Anderson et al., 2007).

6. Conclusions

This paper has highlighted the exergy consumption and emission from different modes of transport within the UK since 1970. Generally speaking exergy consumption has more than doubled for the whole sector while it has significantly increased for most transport modes. Even though exergy efficiency seems to be increasing since the early 1990s this seems to be due to the increasing demand for the more fuel efficient air transport. This can have adverse environmental impacts in the long run. One approach to boost the overall exergy efficiency of the sector with a simultaneous long term decrease of the environmental impact would be the promotion of rail transport, both for passengers and freight, considering its low exergy consumption intensity and exergy emission intensity. Economic incentives to consumers and companies such as cheaper tickets and lower freight charges together with modernization of the existing infrastructure could be instrumental in attaining a modal shift and potentially moving towards a more sustainable transport system.

Regarding environmental impact, there has been a significant decrease in the exergy content of the atmospheric emissions from transport activity as whole since 1970. Correlations between exergy consumed and exergy emitted for each mode of transport imply that this has been influenced to a great extent by technical innovation in road transport that was in turn influenced by the EU environmental standards. However, it is doubtful that technological innovation will be enough to address the escalating problems of fossil fuel depletion and environmental impact resulting from transport activity. That is particularly true for road and air transport that exhibits ever decreasing annual exergy emission intensity reductions suggesting the technological saturation or the diminishing cost-effectiveness of end-of-pipe measures. Policy instruments that could reduce the need for travel as well as behavioral change of the citizens towards choosing less carbon intensive and polluting modes of transport would be an important weapon for tackling the escalating environmental problems.

Acknowledgments

The financial support of the UK Engineering and Physical Science Research Council within the Sustainable Urban Environment Programme is gratefully acknowledged.

References

AEAT, 2007. UK Greenhouse gas inventory, 1990 to 2005. Annual report for submission under the Framework Convention on Climate Change. AEA Technology Plc, Harwell. Available at 〈http://www.airquality.co.uk/archive/reports/cat07/0704261626_ukghgi-90-05_main_chapters_final.pdf〉.

Anderson, K., Bows, A., Footitt, A., 2007. Aviation in a low carbon EU: A research report by the Tyndall Centre, University of Manchester. University of Manchester Tyndall Centre for Climate Change Research (MAXE/MBS), Manchester. Available at 〈http://www.foe.co.uk/resource/reports/aviation_tyndall_07_main.pdf〉.

AQEG, 2007. Air Quality and Climate Change: A UK Perspective. Report of the Expert Group on Air Quality. Department for Food and Rural Affairs, London. Available at 〈http://www.defra.gov.uk/environment/airquality/publications/airqual-climatechange/pdf/fullreport.pdf〉.

Balocco, C., Papeschi, S., Grazzini, G., Basosi, R., 2004. Using exergy to analyse the sustainability of an urban area. Ecolgical Economics 48, 231–244.

Banister, D., 2005. Unsustainable transport: City transport in the new century. Routledge, London.

Banister, D., 2007. Reducing energy use in UK transport. Working paper No. 1028. Oxford University Centre for the Environment, Transport Studies Unit, Oxford.

Bastianoni, S., Marchettini, N., 2000. The problem of co-production in environmental accounting by emergy analysis. Ecological Modelling 129, 187–193.

Bastianoni, S., Nielsen, S.N., Marchettini, N., Jorgensen, S.E., 2005. Use of thermodynamic functions for expressing some relevant aspect of sustainability. International Journal of Energy Research 29, 53–64.

Begg, D., Gray, D., 2004. Transport policy and vehicle emission objectives in the UK: is the marriage between transport and environment policy over? Environmental Science and Policy 7, 155–163.

BERR, 2007a. Energy consumption by final user (energy supplied basis), 1970 to 2006. Department for Business, Enterprise and Regulatory Reform, London. Available at 〈http://www.dti.gov.uk/energy/statistics/source/total/page18424.html〉.

BERR, 2007b. Renewables: Commodity balances. Department for Business, Enterprise and Regulatory Reform, London. Available at 〈http://www.dti.gov.uk/energy/statistics/source/renewables/page18513.html〉.

BERR, 2007c. Digest of United Kingdom Energy Statistics 2006 URN No.: 07/87. Department for Business, Enterprise and Regulatory Reform, London. Available at 〈http://www.berr.gov.uk/energy/statistics/publications/dukes/page39771.html〉.

BERR, 2007d. dti4088 Energy Paper. Department for Business, Enterprise and Regulatory Reform, London. Available at 〈http://www.berr.gov.uk/files/file11257.pdf〉.

BERR, 2007e. Digest of United Kingdom Energy Statistics 2005. URN No 05/87. Department for Business, Enterprise and Regulatory Reform, London. Available at 〈http://www.berr.gov.uk/whatwedo/energy/statistics/publications/dukes/2005/page19311.html〉.

Cleveland, C.J., Kaufmann, R.K., Stern, D.I., 2000. Aggregation and the role of energy in the economy. Ecological Economics 32, 301–317.

Crutzen, P.J., Mosier, A.R., Smith, K.A., Winiwarter, W., 2008. N2O release from agro biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics 8, 389–395.

Daly, H., 1990. Towards some operational principles of sustainable development. Ecological Economics 2, 1–6.

DEFRA, 2005. Securing the future: UK Government sustainable development strategy. Sustainable Development Unit Department for Environment, Food and Rural Affairs, London. Available at 〈http://www.sustainable-development.gov.uk/publications/pdf/strategy/SecFut_complete.pdf〉.

Dincer, I., 2002. The role of exergy in energy policy making. Energy Policy 30, 127–149.

Dincer, I., Hussain, M.M., Al-Zaharnah, I., 2003. Energy and exergy use in the industrial sector of Saudi Arabia. Proceedings of the Institute of Mechanical Engineering Part A: Journal of Power and Energy 217, 481–492.

Dincer, I., Hussain, M.M., Al-Zaharnah, I., 2004. Energy and exergy utilization in transportation sector of Saudi Arabia. Applied Thermal Engineering 24, 525–538.

DfT, 2007a. Transport statistics Great Britain: 2007 edition. Department for Transport, London. Available at 〈http://www.dft.gov.uk/162259/162469/221412/217792/2214291/TSGB2007Final_linksV12.pdf〉.

DfT, 2007b. Transport statistics report: Maritime statistics 2006. Department for Transport, London. Available at 〈http://www.dft.gov.uk/162259/162469/221412/221658/223721/287109/Maritimestatistics2006〉.

DfT, 2007c. Transport trends: 2006 edition. Department for Transport, London. Available at 〈http://www.dft.gov.uk/162259/162469/221412/190425/220778/Trends_2006_FINAL_v5.pdf〉.

DfT, 2007d. Biofuels—risks and opportunities. Department for Transport, London. Available at 〈http://www.dft.gov.uk/pgr/roads/environment/rtfo/289579〉.

Doornbosch, S., Steenblik, R., 2007. Biofuels: is the cure worse than the disease? Report SG/SD/RT(2007)3. Organisation for Economic Cooperation and Development, Paris. Available at 〈http://www.ethanolrfa.org/objects/documents//070911oecdonbiofuels.pdf〉.

DTI, 2006. Energy consumption in the United Kingdom. URN No.: 02/1049. Department of Trade and Industry, London. Available at 〈http://www.berr.gov.uk/files/file11250.pdf〉.

EC, 2008. Consolidated Versions of the Treaty on European Union and the Treaty on the Functioning of the European Union. Official Journal of the European Union 2008/C 115/01-115/388. Available at 〈http://eur-lex.europa.eu/JOHtml.do?uri=OJ:C:2008:115:SOM:EN:HTML〉.

Ediger, V.Ş., Çamdali, Ü., 2007. Energy and exergy efficiencies in Turkish transportation sector, 1988–2004. Energy Policy 35, 4044–4088.

Ertesvag, I.S., 2001. Society exergy analysis: a comparison of different societies. Energy 26, 253–270.

Ertesvag, I.S., Mienik, M., 2000. Exergy analysis of the Norwegian society. Energy 25, 957–973.

Farber, C.S., Costanza, R., Wilson, M.A., 2002. Economic and ecological concepts for valuing ecosystem services. Ecological Economics 41, 375–392.

Gasparatos, A., El-Haram, M., Horner, M., 2008. A critical review of reductionist approaches for assessing the progress towards sustainability. Environmental Impact Assessment Review 28, 286–311.

Gasparatos, A., El-Haram, M., Horner, M., in press a. The argument against a reductionist approach for measuring sustainable development performance and the need for methodological pluralism. Accounting Forum. doi:10.1016/j.accfor.2008.07.006.

Gasparatos, A., El-Haram, M., Horner, M., in press b. Assessing the sustainability of the UK society using thermodynamic concepts: Part 2. Renewable and Sustainable Energy Reviews, doi:10.1016/j.rser.2008.03.005.

Glaister, S., 2002. UK Transport Policy 1997–2001. Oxford Review of Economic Policy 18, 154–186.

Hammond, G.P., 2004a. Towards sustainability: energy efficiency, thermodynamic analysis and the two cultures. Energy Policy 32, 1789–1798.

Hammond, G.P., 2004b. Engineering sustainability: thermodynamics, energy systems, and the environment. International Journal of Energy Research 28, 613–639.

Hammond, G.P., Stapleton, A.J., 2001. Energy analysis of the United Kingdom energy system. Proceedings of the Institute of Mechanical Engineering Part A: Journal of Power and Energy 215, 141–162.

Ji, X., Chen, G.Q., 2006. Exergy analysis of energy utilization in the transportation sector in China. Energy Policy 34, 1709–1719.

Koroneos, C.J., Nanaki, E.A., 2007. Energy and exergy utilization assessment of the Greek transport sector. Resources Conservation and Recycling 52, 700–706.

Kotas, T.J., 1985. The exergy method of thermal plant analysis. Anchor Brendon Ltd, Tiptree.

NAEI, 2007. Emission Statistics by UNECE Source Category—Summary Tables. London: National Atmospheric Emission Inventory. Available at 〈http://www.naei.org.uk/emissions/emissions_2004.php?〉action = unece and options = 1PAY(last accessed Dec. 2007).

Nakicenovic, N., Gilli, P.V., Kurtz, R., 1996. Regional and global exergy and energy efficiencies. Energy 21, 223–237.

Patterson, M., 1998. Commensuration and theories of values in ecological economics. Ecological Economics 25, 105–125.

Rosen, M.A., Dincer, I., 1999. Exergy analysis of waste emissions. International Journal of Energy Research 23, 1153–1163.

Rosen, M.A., Dincer, I., 2001. Exergy as the confluence of energy, environment and sustainable development. Exergy, An International Journal 1, 3–13.

Rosen, M.A., Dincer, I., Kanoglu, M., 2008. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Energy Policy 36, 128–137.

Saidur, R., Sattar, M.A., Masjuki, H.H., Ahmed, S., Hashim, U., 2007. An estimation of the energy and exergy efficiencies for the energy resources consumption in the transportation sector in Malaysia. Energy Policy 35, 4018–4026.

Sciubba, E., Ulgiati, S., 2005. Emergy and exergy analyses: Complementary methods or irreducible ideological options? Energy 30, 1953–1988.
Szargut, J., Morris, D.R., Stewart, F.R., 1988. Exergy analysis of thermal chemical and metallurgical processes. Hemisphere Publishing Corporation, New York.
Tapio, P., Banister, D., Luukkanen, J., Vehmas, J., Willamo, R., 2007. Energy and transport in comparison: Immaterialisation, dematerialisation, and decarbonisation in the EU15 between 1970 and 2000. Energy Policy 32, 433–451.
T&E, 2007. Reducing CO^2 emissions from new cars 2006. Progress report on the car industry's voluntary commitment. European Federation for Transport and the Environment, Brussels, Available online at 〈http://www.transportenvironment.org/docs/Publications/2007/2007-09_progress_voluntary_commitment_2006.pdf〉.
TNS, 2000. The natural step framework guidebook. The Natural Step New Zealand, Christchurch. Available at 〈http://www.naturalstep.org.nz/downloads/TNSFrameworkGuidebook.pdf〉.
Ulgiati, S., Raugei, M., Bargigli, S., 2006. Overcoming the inadequacy of single criterion approaches to Life Cycle Assessment. Ecological Modelling 190, 432–442.
Utlu, Z., Hepbasli, A., 2006. Assessment of the energy utilization efficiency in the Turkish transportation sector between 2000 and 2020 using energy and exergy analysis method. Energy Policy, 1611–1618.
Utlu, Z., Hepbasli, A., 2007. Parametrical investigation of the effect of dead (reference) state on energy and exergy utilization efficiencies of residential–commercial sectors: a review and an application. Renewable and Sustainable Energy Reviews 11, 603–634.
Wall, G., 1990. Exergy Conversion in the Japanese Society. Energy 15, 435–444.